

Award Number: DAMD17-00-1-0115

TITLE: Targeting of Adenovirus Vectors to Breast Cancer Mediated
by Soluble Receptor-Ligand Fusion Proteins

PRINCIPAL INVESTIGATOR: Igor P. Dmitriev Ph.D.

CONTRACTING ORGANIZATION: University of Alabama at Birmingham
Birmingham, Alabama 32594-0111

REPORT DATE: June 2001

TYPE OF REPORT: Annual report

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for public release;
Distribution unlimited

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 2001	3. REPORT TYPE AND DATES COVERED Annual (15 May 00 - 14 May 01)	
4. TITLE AND SUBTITLE Targeting of Adenovirus Vectors to Breast Cancer Mediated by Soluble Receptor-Ligand Fusion Proteins			5. FUNDING NUMBERS DAMD17-00-1-0115	
6. AUTHOR(S) Igor P. Dmitriev, Ph.D.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Alabama at Birmingham Birmingham, Alabama 32594-0111 E-Mail: idmitriev@gtg.ccc.uab.edu			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Materiel Command Fort Detrick, Maryland 21702-5012			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited				12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 Words) The use of adenovirus (Ad) vectors for cancer gene therapy applications is currently limited due to the broad viral tropism associated with the widespread expression of primary coxsackievirus and adenovirus receptor (CAR) in human tissues. To confer Ad targeting capability to relevant cell types we have proposed the use of soluble CAR ectodomain (sCAR) fused with ligand to block CAR-mediated tropism and simultaneously achieve infection through a novel receptor overexpressed on target cells. To target Ad vectors to breast cancer cell types we produced bispecific proteins containing sCAR and either α_v -integrin-binding RGD-4C or NGR peptide motif possessing high potential for bacteriophage targeting to human breast cancer xenografts in mice. Specifically, we designed gene encoding sCAR, purification tag, phage T4 fibrin polypeptide, hinge region and site for cloning of ligand sequences. Incorporation of fibrin polypeptide provided trimerization of sCAR-fusion proteins that resulted in augmented affinity to Ad fiber knob domain and increased ability to block CAR-mediated Ad infection compared to monomeric sCAR protein. We also demonstrated that most of breast cancer cell lines tested display low CAR and high levels of α_v -integrins. Thus, utilization of constructed trimeric sCAR-ligand proteins for Ad targeting may augment Ad vectors potency for breast cancer treatment.				
14. SUBJECT TERMS Cancer therapy, gene therapy, adenovirus, targeting, scar-fusion proteins				15. NUMBER OF PAGES 23
				16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Table of Contents

Cover.....	1
SF 298.....	2
Introduction.....	4
Body.....	4-12
Key Research Accomplishments.....	13
Reportable Outcomes.....	13
Conclusions.....	14
References.....	15
Appendices.....	16-23

INTRODUCTION

One of the major challenges facing Adenovirus (Ad) gene delivery system is the alteration of broad native viral tropism in order to confer targeting capability to relevant cell types. Broad viral tropism is predicated by expression of primary cellular receptor, coxsackievirus group B and adenovirus receptor (CAR) (1), in a wide range of human tissues (2). The limitations of Ad vectors associated with broad CAR-dependent tropism and inefficient gene delivery to CAR-deficient cells could be solved by providing alternative mechanism of Ad binding to target cells. We recently have proposed Ad targeting approach based on utilization of soluble CAR ectodomain fused with targeting ligand to achieve both virus linkage and blocking of CAR-mediated tropism and simultaneously redirect Ad to an alternative receptor. Thus, the infection of cells by this virus complex would not be dependent on CAR presence on a target cell membrane. For the proof of principle we have constructed soluble CAR fused with EGF and demonstrated that sCAR-EGF protein provides effective Ad targeting to multiple cell types overexpressing EGFR with enhancement of infection efficiency (3). We also demonstrated that sCAR-EGF enables several-fold augmentation of Ad gene transfer to both primary and established pancreatic carcinoma EGFR-positive cell lines (4). Similar approach was successfully used to target Ad to high-affinity Fcγ receptor I-positive human monocytic cells (5). Thus, employment of recombinant sCAR-fusion proteins might offer advantages to expand targeting capabilities of Ad vectors due to ablation of broad viral tropism and providing novel tropism to the target cells.

BODY

Task 1. To design bispecific soluble sCAR-ligand fusion proteins possessing the capacity to achieve high efficacy binding both to Ad fiber protein and surface receptor on breast cancer cells

Design of sCAR-ligand proteins. It was shown that soluble extracellular domain of CAR bound to representatives of all Ad subgroups except subgroup B (6). Both structural analysis of fiber knob-CAR complexes and knob domain mutagenesis showed that there are three CAR-binding sites on the fiber knob domain (7). Further kinetic analysis of Ad2 fiber knob binding to the CAR D1 domain revealed that an avidity mechanism corresponds to trimeric receptor-ligand interaction (8). To take an advantage of trivalent nature of CAR-knob binding for Ad targeting, we proposed to derive recombinant protein consisting of soluble CAR in fusion with

trimerization sequence and a targeting ligand. Our goal was to generate a trimeric sCAR-ligand molecules that could provide high affinity linkage between Ad vector and cellular target receptor. Predicted CAR-knob binding ratio may increase linkage efficiency of trimeric sCAR-ligand fusion proteins with virus particles and thereby contribute to the ligand-mediated binding of such viral complexes to target receptors. In order to achieve trimerization of sCAR-fusion molecules, we choose to employ polypeptide derived from bacteriophage T4 fibritin protein forming highly stable homotrimers. As targeting ligands we proposed to use an α_v -integrin-binding RGD-4C peptide (CDCRGDCFC) and NGR peptide motif (CNGRCVSGCAGRC) initially isolated by phage biopanning (9). Phage displaying an RGD-containing peptide when injected intravenously into tumor-bearing mice was detected in melanoma and breast carcinoma tumor blood vessels, but not in normal tissues (10). NGR peptide coupled with doxorubicin was shown to have more potent effects against metastatic human breast cancer xenografts than the free drug (11). TNF fused with CNGRC peptide also was shown to induce stronger antitumor effects in animal models than TNF alone (12). To produce CAR-ligand fusion proteins a baculovirus expression system that has already proved its utility for the expression of functional soluble CAR (6) and sCAR-EGF chimera (3) was used.

Construction of recombinant plasmids. The donor plasmid for the generation of recombinant baculoviruses expressing sCAR-ligand fusion proteins was made as follows. To generate a recombinant gene encoding the extracellular domain of human CAR followed by polypeptide sequence derived from bacteriophage T4 fibritin protein (13), PCR was used. Sense primer 5' GTT GAA AGA TCT GGA TTA ACC AAT AAA ATA AAA GCT ATC GAA ACT GAT ATT GCA TCA G complementary to the position 1240 of the fibritin gene was designed to introduce *Bgl*II restriction site into amplified DNA sequence, and antisense primer 5' TTG CGG CCC CAG CGG CCG CTG GTG ATA AAA AGG TAG complementary to the position 16 of untranslated 3'-region was designed both to introduce *Not*I and substitute stop codon for alanine (GCC) codon. The PCR-derived 238-bp DNA fragment was digested with *Bgl*II and *Not*I, and 214-bp DNA fragment encoding 71 carboxy-terminal amino acids (aa) of fibritin M polypeptide (13) was purified. To construct the recombinant gene coding for extracellular CAR, six histidines, and short flexible linker fused with fibritin coding sequence *Bgl*II-*Not*I-fragment was ligated with plasmid pFBshCAR-EGF (3) digested with *Bam*HI and *Not*I substituting EGF for fibritin. Resultant plasmid designated pFBsCARf was cleaved with *Not*I and ligated with oligonucleotide duplex 5' GGC CCA ACC GCA GCC AAA ACC TCA ACC CCA GCC ACA ACC TCA GCC CAA ACC TCA GCC TAA ACC GGT TTA AAC GGC C coding for proline-rich hinge region derived from camel immunoglobulins and containing *Age*I site followed by stop

codon. Plasmid clone containing hinge DNA fragment in correct orientation was selected by sequencing and designated pFBsCARfCh. The constructed plasmid was then used as a vector to generate the recombinant baculovirus to produce sCARf control protein. Oligonucleotides 5' CCG GGA GCT CTG CGC TAG CT and 5' CCG GAG CTA GCG CAG AGC TC designed to contain *Nhe*I site and *Age*I compatible cohesive 5'-ends were annealed to form DNA duplex and ligated with *Age*I-digested pFBsCARfCh. Plasmid clones were sequenced, and the plasmid containing the duplex in the correct orientation was designated pFBsCARfMCS. The resultant plasmid contains recombinant gene coding for sCAR, six-His tag, flexible linker, fibrin polypeptide, proline-rich hinge, and multiple cloning site (MCS) to facilitate downstream incorporation of ligand sequences (Fig. 1).

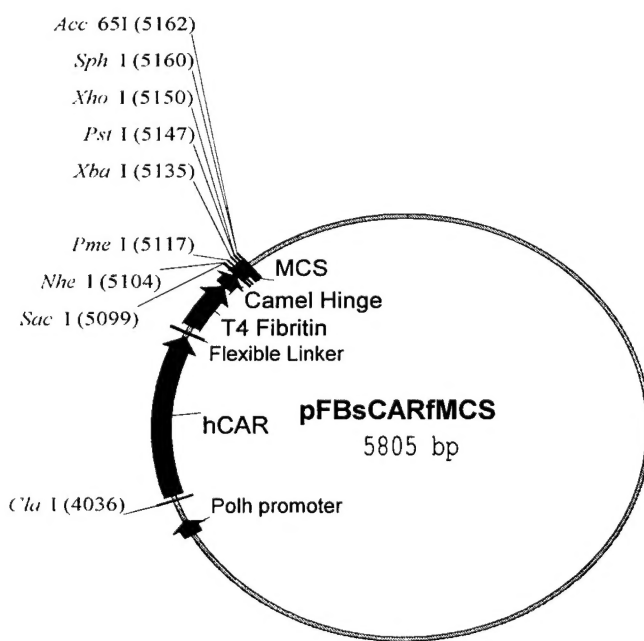


Figure 1. Circular map of the plasmid vector pFBsCARfMCS. Plasmid contains recombinant gene encoding human CAR ectodomain (hCAR), flexible linker, trimerization domain from phage T4 fibrin protein (T4 fibrin), proline-rich hinge region from camel immunoglobulins, and multiple cloning site for incorporation of ligand sequences (MCS) under control of baculovirus polyhedrin promoter (Polh promoter).

The plasmids coding for the sCAR fused with either RGD-4C or NGR peptide motifs were made as follows. To incorporate the RGD-4C peptide into the carboxy terminus of sCARf fusion protein, oligonucleotides 5' TGC GAC TGT CGC GGG GAT TGC TTT TGT GG 3' and 5' CTA GCC ACA AAA GCA ATC CCC GCG ACA GTC GCA AGC T 3' were designed to form DNA duplex coding for **ACDCRGDCFCG** followed by in-frame stop codon. To incorporate the NGR peptide, oligonucleotides 5' TGC AAC GGA AGG TGT GTAAGC GGG TGC GCG GGC AGA TGC GG 3' and 5' CTA GCC GCA TCT GCC CGC GCA CCC GCT TAC ACA CCT TCC

5' GTT GCA AGC T 3' were designed to form DNA duplex coding for **ACNGRCVSGCAGRCG** and stop codon. In addition, both generated DNA duplexes contained *SacI*- and *NheI*-compatible cohesive ends designed to fuse the sCAR-fibritin ORF with peptide coding sequences. The oligonucleotide duplexes were cloned into *SacI* and *NheI*-digested pFBsCARfMCS, DNA clones were sequenced in the region of insert and the plasmids containing RGD-4C and NGR coding sequences in the correct orientation were designated pFBsCARf-RGD4C and pFBsCARf-NGR respectively. The constructed plasmids encoding sCAR-fibritin protein fused with peptide ligands were then used as vectors to generate the recombinant baculovirus genomes using the Bac-to-Bac baculovirus system (Life Technologies, Grand Island, N.Y.). To produce sCARf-RGD4C and sCARf-NGR fusion proteins, generated recombinant baculoviruses were used to infect insect cells.

Expression and purification of sCAR-fusion proteins. The fusion proteins sCARf, sCARf-RGD4C and sCARf-NGR were expressed in High Five cells (Invitrogen, Carlsbad, Calif.) infected with recombinant baculoviruses as described previously (3). Baculovirus infections resulted in high expression levels of secreted soluble sCARf, sCARf-RGD4C and sCARf-NGR fusion proteins. Secreted His₆-tagged proteins were purified from dialyzed culture medium by immobilized metal ion affinity chromatography (IMAC) on Ni-nitrilotriacetic acid (NTA)-Sepharose (Qiagen, Valencia, Calif.) as recommended by the manufacturer. Protein concentrations were determined by the BCA-200 protein assay kit (Pierce, Rockford, IL) with bovine gamma globulin as the standard. Purified sCARf, sCARf-RGD4C and sCARf-NGR proteins were then analyzed for trimerization and presence of encoded polypeptide sequences.

Structure of recombinant sCAR-fusion proteins. To characterize structure and composition of recombinant proteins gel electrophoresis and Western blot were used. To determine whether generated sCAR-fusion proteins could form trimers, these proteins were analyzed by SDS-PAGE. Electrophoretic separation of boiled protein samples showed the presence of major bands migrating as was expected for monomeric forms of sCARf, sCARf-RGD4C, and sCARf-NGR proteins with molecular masses of 36.0, 36.7 and 37.0 kDa respectively (Fig. 2). Electrophoretic mobility of unboiled protein samples was decreased and close to those predicted for trimeric forms of sCARf, sCARf-RGD4C, and sCARf-NGR proteins. This result demonstrated that fibritin polypeptide incorporated in the context of recombinant molecule is capable of providing an efficient trimerization of sCAR-fusion proteins.

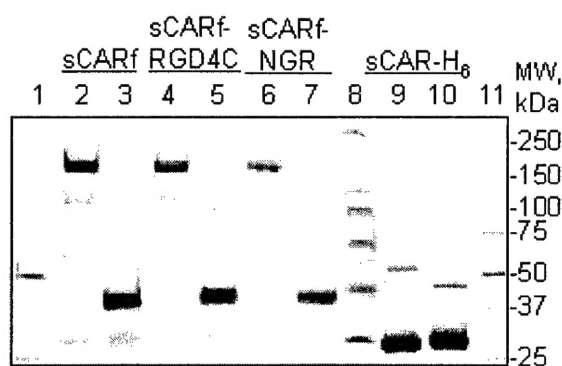


Figure 2. Trimerization analysis of sCAR-fusion proteins by polyacrylamide gel electrophoresis. Samples of purified sCARf (lanes 2, 3), sCARf-RGD4C (lanes 4, 5), sCARf-NGR (lanes 6, 7), sCAR-H₆ (lanes 9, 10), and molecular mass markers (lanes 1, 8, 11) were separated on 4-15% gradient SDS gel. The samples in lanes 3, 5, 7, and 10 were boiled in Laemmli loading buffer to denature proteins to monomers, while lanes 2, 4, 6, and 9 contain unboiled proteins in their native conformation. Protein bands were visualized by GELCODE blue stain reagent (Pierce, Rockford, IL). The numbers on the right indicate molecular masses of marker proteins in kilodaltons (kDa).

Western blot analysis of protein composition using monoclonal antibodies to sCAR protein revealed the presence of CAR ectodomain in the context of each sCAR-fusion protein (Fig. 3).

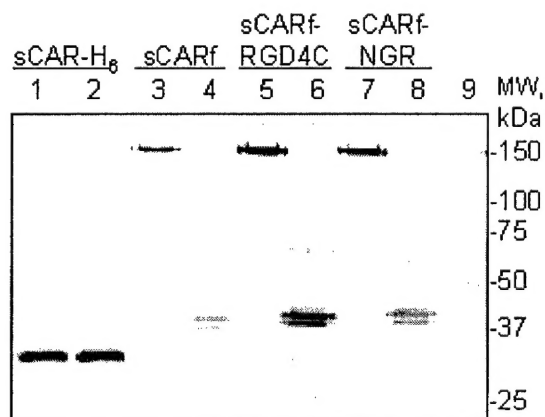


Figure 3. Western blot analysis of sCAR-fusion proteins. Samples of purified sCAR-H₆ (lanes 1, 2), sCARf (lanes 3, 4), sCARf-RGD4C (lanes 5, 6), sCARf-NGR (lanes 7, 8) were boiled in Laemmli loading buffer and separated on 4-15% gradient SDS gel. Electrophoretically resolved proteins were transferred to PVDF membrane probed with MAb to soluble CAR ectodomain and then detected with goat anti-mouse antibody-Alkaline Phosphatase conjugate (Sigma). The numbers on the right indicate molecular masses of marker proteins (lane 9) in kilodaltons (kDa).

These results suggest that derived proteins are able to maintain both designed composition and stable trimeric structure. Thus, we obtained preparative amounts of purified sCARf, sCARf-RGD4C and sCARf-NGR trimeric fusion protein for subsequent experiments.

Analysis of sCAR-fusion proteins binding to Ad5 fiber knob. We first chose to characterize trimeric sCARf protein with respect to its ability to bind Ad fiber knob domain

compare to sCAR-His₆ monomer generated previously (3). To compare fiber knob binding efficiencies of sCARf and sCAR-His₆ we used an ELISA. This assay showed that trimeric sCARf protein efficiently bound to immobilized Ad5 fiber knob (Fig. 4).

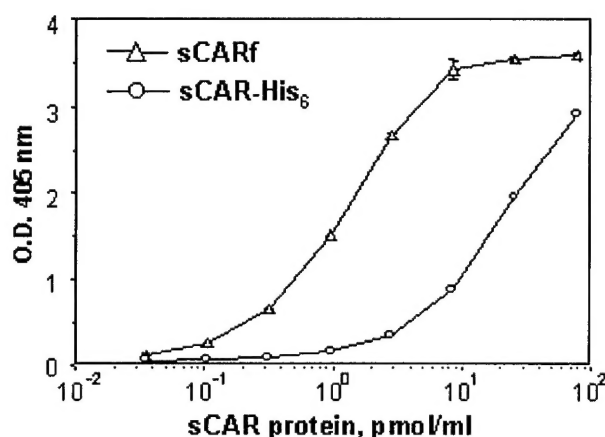


Figure 4. ELISA analysis of sCAR-fusion proteins binding to Ad5 fiber knob. Purified trimeric sCARf and monomeric sCAR-His₆ proteins were incubated at various concentrations with recombinant Ad5 fiber protein immobilized on an ELISA plate. Bound sCAR-fusion proteins were probed with MAb against soluble CAR ectodomain and then detected with goat anti-mouse antibody-Alkaline Phosphatase conjugate (Sigma). Each point represents the cumulative mean \pm SD of triplicate determinations. Some error bars depicting standard deviations are smaller than the symbols.

Compare to the monomeric sCAR-His₆ control protein, the affinity of sCARf-knob binding was greatly increased in a wide range of used concentrations. Based on the obtained result, whereby generated sCARf protein is able of high affinity binding to fiber knob domain, we hypothesized that trimeric sCAR-fusion proteins may be of utility to block CAR-mediated virus-cell attachment and Ad infection.

Analysis of sCAR-fusion proteins ability to block Ad infection. In order to evaluate whether improved knob binding results in increased ability of trimeric sCAR-fusion proteins to block Ad infection, we performed an infection inhibition assay. Recombinant AdCMVLuc vector expressing luciferase gene was preincubated with one of the sCAR-His₆, sCARf-RGD4C, or sCARf-NGR at increasing concentrations or PBS and used to infect 293 cells known to express high level of CAR (Fig. 6). The ability of sCAR fusion proteins to block viral infection was assessed by sCAR protein dose dependent impairment of Ad-mediated gene transfer as measured by luciferase activity of infected cells (Fig. 5). It was shown that, compare to monomeric sCAR-His₆ protein, both sCARf-RGD4C and sCARf-NGR displayed an increased ability to inhibit CAR-mediated Ad infection. The concentrations of sCARf-RGD-4C, sCARf-NGR and sCAR-His₆ needed to compete Ad infection by 50% were 3, 6, and 54 nM respectively. This experiment demonstrated that trimeric sCAR-fusion proteins possessed

superior ability to inhibit Ad infection in comparison with sCAR-His₆ monomer. This finding validated the utility of produced sCAR-RGD4C and sCARf-NGR trimeric fusion proteins in order to block Ad native tropism and, therefore, provided a rationale for further Ad targeting studies.

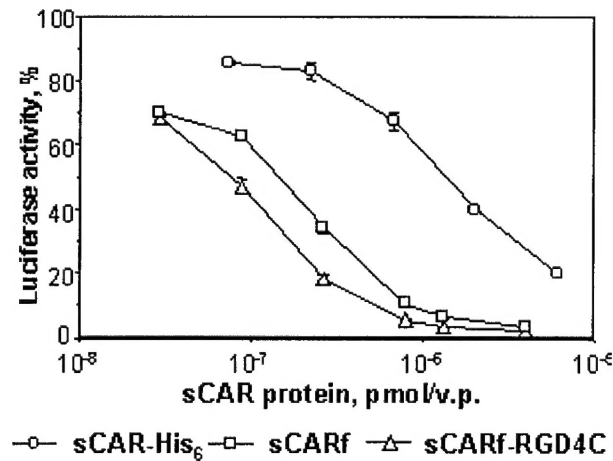


Figure 5. Inhibition of Ad-mediated gene transfer. AdCMVluc vector was mixed with either PBS or varying amounts of sCAR-His₆, sCARf or sCAR-RGD4C fusion proteins and incubated for 15 min at room temperature. Viral mixtures were diluted to 1 ml with infection medium and 200- μ l aliquots were added to monolayers of 293 cells grown in a 24-well plate (5×10^5 cells/well) at MOI of 100 v.p./cell. After 45-min incubation at room temperature to allow virus internalization infection medium was aspirated, the cells were washed with PBS, and a growth medium was added. The cells were incubated at 37°C to allow expression of the reporter genes. Twenty four hours postinfection the cells were lysed and luciferase activity was analyzed by using the Promega (Madison, Wis.) luciferase assay system and a Berthold (Gaithersburg, Md.) luminometer. Luciferase activities detected in cells infected in the presence of sCAR-fusion proteins are shown as percentages of luciferase activity registered in control cells infected with AdCMVluc mixed with PBS. Each point represents the cumulative mean \pm SD of triplicate determinations. Some error bars depicting standard deviations are smaller than the symbols.

Task 2. Evaluate the ability and efficacy of sCAR-ligand fusion proteins for targeted gene delivery to breast carcinoma cells *in vitro*

Analysis of breast cancer cell lines for CAR and α_V -integrins expression. In order to conduct further Ad targeting studies *in vitro* we analyzed several breast adenocarcinoma cell lines for expression levels of cell surface receptors involved in Ad infection, i.e. CAR and α_V -integrins. The following established breast cancer cell lines AU-565, SK-BR-3, BT-474, MCF-7, ZR-75-1, MB-468, and GI-101A were characterized for expression of CAR, α_V -, and $\alpha_V\beta_5$ -integrins by indirect immunofluorescence assay. Our previous studies showed that most of these cells display a low susceptibility to Ad infection. These findings were corroborated with flow cytometry data that demonstrated either absence or low level of CAR expression on cell

surface (Fig. 6). Importantly, high levels of integrins detected in these cell lines suggests that poor susceptibility due to the lack of CAR might be overcome by Ad targeting to α_V -integrins present at sufficient magnitude.

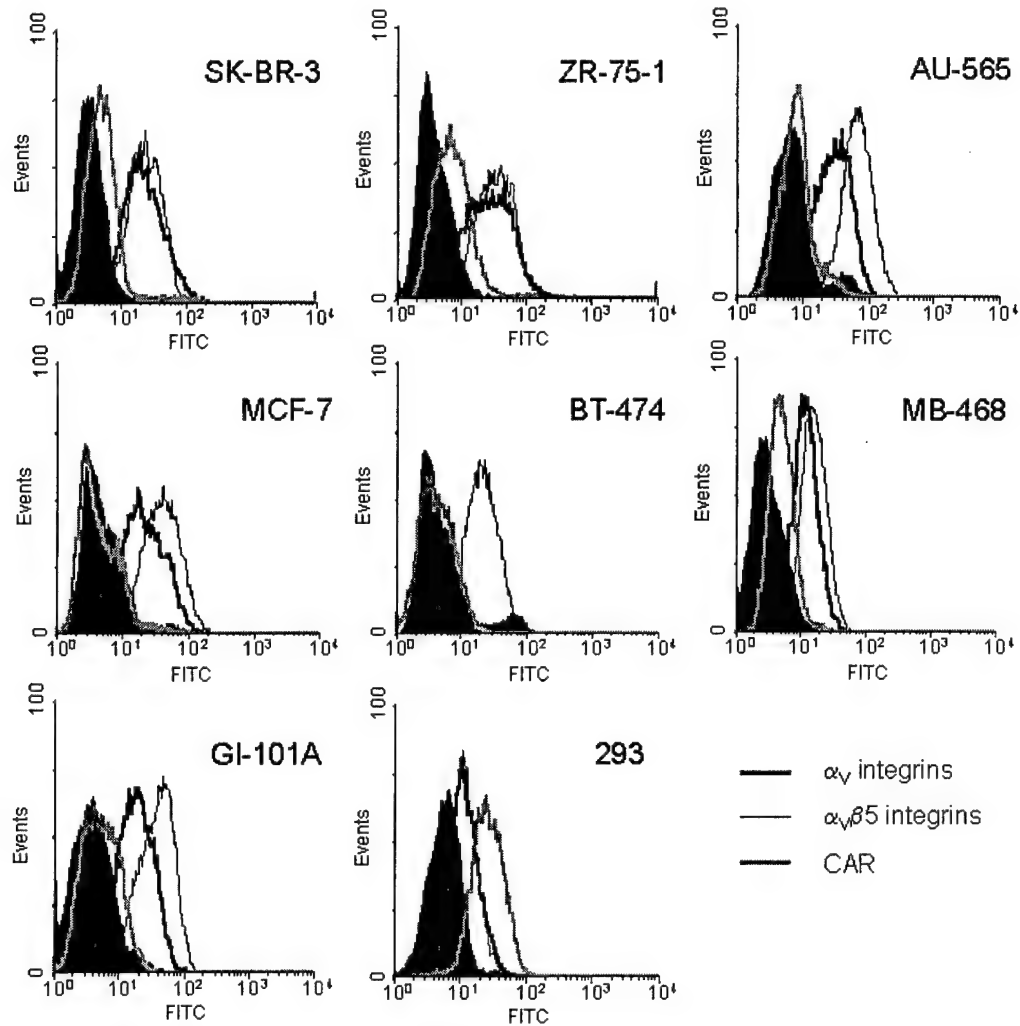


Figure 6. Expression of CAR and α_V -integrins in breast cancer cell lines. The established breast adenocarcinoma cell lines AU-565, SK-BR-3, BT-474, MCF-7, ZR-75-1, MB-468, GI-101A and control 293 human kidney cell line were analyzed for CAR expression by indirect immunofluorescence assay using anti-CAR RmcB MAb. Expression of α_V - and $\alpha_V\beta_5$ -integrins was analyzed by using MAB1953 and MAB1961 antibodies (Chemicon, Temecula, CA) respectively. Positive staining with anti-CAR (bold gray line), anti- α_V - (bold black line) or anti- $\alpha_V\beta_5$ -integrins antibody (thin black line) is seen relative to an isotype control (black-filled spike). A representatives of three separate experiments are shown.

To this end, we have shown that recombinant Ad vector containing fibers genetically modified to incorporate RGD-4C motif is capable of augmented gene delivery to multiple cell types through the use of α_V -integrins (4, 14). However, this vector possessed an extended tropism capacity without specificity restricted to selected target cell types. Of note, the use of recombinant sCAR-ligand fusion proteins enables to block CAR-mediated tropism and redirect

Ad to the alternative receptor overexpressed on target cells (3 - 5). Thus, this experiment established a panel of breast cancer cell lines expressing a high levels of target receptor for further Ad targeting studies *in vitro*.

KEY RESEARCH ACCOMPLISHMENTS

- Plasmid vector was constructed that contains recombinant gene encoding soluble CAR ectodomain, six-His purification tag, phage T4 fibrin polypeptide, hinge region and site for cloning of ligand sequences.
- Recombinant fusion proteins containing sCAR, fibrin trimerization domain and either RGD-4C or NGR peptide ligands were produced using baculovirus expression system and purified.
- Produced fusion proteins sCARf, sCARf-RGD4C, and sCARf-NGR were shown to form stable trimers and maintain designed composition.
- Trimeric sCAR-fusion proteins were shown to possess an augmented affinity to Ad fiber knob domain and increased ability to block CAR-mediated Ad infection compared to monomeric sCAR protein.
- Set of established breast cancer cell lines AU-565, SK-BR-3, BT-474, MCF-7, ZR-75-1, MB-468, and GI-101A was characterized for expression levels of CAR and α_V -integrins.

REPORTABLE OUTCOMES

The following manuscript was accepted for publication in Gene Therapy:

Wesseling, J. G., P. J. Bosma, V. Krasnykh, E. A. Kashentseva, J. L. Blackwel, P. N. Reynolds, H. Li, M. Parameshwar, S. M. Vickers, E. M. Jaffee, K. Huibregtse, D. T. Curiel, and I. P. Dmitriev. 2001. Improved gene transfer efficiency to primary and established human pancreatic carcinoma target cells via epidermal growth factor receptor and integrin targeted adenoviral vectors. *Gene Ther.* 8:In Press.

CONCLUSIONS

In conclusion, the work presented in this report completely addressed task 1 outlined in the approved Statement of Work. To confer Ad targeting capability to breast cancer cell types we produced bispecific proteins containing soluble CAR in fusion with targeting ligand. Specifically, the recombinant genes encoding sCAR, purification tag, phage T4 fibrin polypeptide, hinge region and either α_v -integrin-binding RGD-4C or NGR peptide motif were designed and expressed by using baculovirus system. We showed that incorporation of fibrin polypeptide provided trimerization of sCAR-RGD4C, sCAR-NGR and control sCARf fusion proteins. These trimeric sCAR-fusion proteins demonstrated an augmented affinity to Ad fiber knob domain and increased ability to block CAR-mediated Ad infection compared to monomeric sCAR-H₆ protein. To partially address task 2 outlined in the approved Statement of Work analysis of breast cancer cell lines for expression level of CAR and α_v -integrins was performed. We demonstrated that most of the established breast cancer cell lines tested display low CAR and high levels of α_v -integrins. Thus, high levels of integrins detected on breast cancer cells suggested that poor Ad susceptibility due to the lack of CAR might be overcome by Ad vector targeting to α_v -integrins present at sufficient magnitude.

REFERENCES

1. J. M. Bergelson *et al.*, *Science* **275**, 1320-3 (1997); J. M. Bergelson, *Biochem Pharmacol* **57**, 975-9 (1999).
2. R. P. Tomko, R. Xu, L. Philipson, *Proc Natl Acad Sci U S A* **94**, 3352-6 (1997).
3. I. Dmitriev, E. Kashentseva, B. E. Rogers, V. Krasnykh, D. T. Curiel, *J Virol* **74**, 6875-84 (2000).
4. J. G. Wesseling *et al.*, *Gene Therapy* **8**, In Press (2001).
5. C. Ebbinghaus *et al.*, *J Virol* **75**, 480-9 (2001).
6. P. W. Roelvink *et al.*, *J Virol* **72**, 7909-15 (1998).
7. P. W. Roelvink, G. Mi Lee, D. A. Einfeld, I. Kovesdi, T. J. Wickham, *Science* **286**, 1568-71 (1999); M. C. Bewley, K. Springer, Y. B. Zhang, P. Freimuth, J. M. Flanagan, *Science* **286**, 1579-83 (1999).
8. H. Lortat-Jacob, E. Chouin, S. Cusack, M. J. van Raaij, *J Biol Chem* **276**, 9009-15 (2001).
9. E. Koivunen, B. Wang, E. Ruoslahti, *J Cell Biol* **124**, 373-80 (1994).
10. R. Pasqualini, E. Koivunen, E. Ruoslahti, *Nat Biotechnol* **15**, 542-6 (1997).
11. W. Arap, R. Pasqualini, E. Ruoslahti, *Science* **279**, 377-80 (1998).
12. F. Curnis *et al.*, *Nat Biotechnol* **18**, 1185-90 (2000).
13. S. V. Strelkov, Y. Tao, M. M. Shneider, V. V. Mesyanzhinov, M. G. Rossmann, *Acta Crystallogr D Biol Crystallogr* **54**, 805-16 (1998).
14. K. Kasono *et al.*, *Clin Cancer Res* **5**, 2571-9 (1999); J. L. Blackwell *et al.*, *Hum Gene Ther* **11**, 1657-69 (2000); V. Krasnykh *et al.*, *Cancer Res* **60**, 6784-7 (2000); T. J. Vanderkwaak *et al.*, *Gynecol Oncol* **74**, 227-34 (1999); I. Dmitriev *et al.*, *J Virol* **72**, 9706-13 (1998).



RESEARCH ARTICLE

Improved gene transfer efficiency to primary and established human pancreatic carcinoma target cells via epidermal growth factor receptor and integrin-targeted adenoviral vectors

JG Wesseling¹, PJ Bosma¹, V Krasnykh², EA Kashentseva², JL Blackwell², PN Reynolds², H Li², M Parameshwar², SM Vickers³, EM Jaffee⁴, K Huibregtse⁵, DT Curiel² and I Dmitriev²

¹Department of Experimental Hepatology, ²Department of Gastroenterology and Liver Diseases, Academic Medical Center, University of Amsterdam, Amsterdam, The Netherlands; ³Division of Human Gene Therapy, Departments of Medicine, Pathology, and Surgery and the Gene Therapy Center and ⁴Department of General Surgery, School of Medicine, University of Alabama at Birmingham, Birmingham, AL; and ⁵Department Of Oncology, Johns Hopkins University School of Medicine, Baltimore, MD, USA

In this study we analyzed two ways of retargeting of Ad-vectors to human pancreatic carcinoma with the aim of enhancing the gene transfer efficiency. First, we analyzed the expression of the epidermal growth factor receptor (EGFR) on primary, as well as established pancreatic carcinoma cells by flow cytometry which revealed high expression levels of EGFR on the surface of these cells. We showed that EGFR-retargeted entry pathway using a bispecific fusion protein formed by a recombinant soluble form of truncated Coxsackie and Adenovirus Receptor (sCAR) genetically fused with human EGF (sCAR-EGF) redirects them to the EGFR leading to an enhanced gene transfer efficiency

to pancreatic carcinoma cells. Since flow cytometry revealed absence of CAR expression, but the presence of at least one of both α v integrins on the pancreatic carcinoma cells, a second way of targeting was investigated using a genetically modified Ad vector which has an RGD (Arg-Gly-Asp)-containing peptide inserted into the HI-loop of the fiber knob. This RGD targeted Ad (AdlucRGD) revealed efficient CAR-independent infection by allowing binding to cellular integrins resulting in a dramatic enhancement of gene transfer. These findings have direct relevance for Ad-vector based gene therapy strategies for pancreatic carcinoma. Gene Therapy (2001) ●, 000-000.

Keywords: pancreatic carcinoma; primary tumor cells; adenovirus vector; targeting; gene therapy

Introduction

Pancreatic cancer is highly aggressive and ranks fifth among malignancy-associated deaths. Prognosis remains dismal because diagnosis of pancreatic cancer is made late in the clinical course of the disease. Currently, there is no effective treatment for this disease: resection is only available to a small fraction of patients presenting with locally confined tumor.¹ Chemotherapy and radiation also have limited effects on patient survival. Adjuvant combined radiochemotherapy might potentially improve survival and can be considered in unresectable, locally advanced disease. However, the role of chemotherapy in advanced disease is exclusively palliative.¹ Therefore, development of new therapeutic modalities such as gene therapy are necessary to improve patient outcome and serve as a more effective treatment for pancreatic cancer.

Adenoviral vectors have been used for both *in vitro* and *in vivo* gene delivery of pancreatic cancer, mainly because

of their ability to infect both dividing pancreatic cancer cells, as well as nondividing tumor cells. Another advantage is that the techniques to produce high-titered preparations of adenovirus vectors are relatively simple. Furthermore, phase I clinical trials employing adenovirus vectors have been started already for pancreatic cancer.² As observed for other tumor tissue types, a major concern associated with using adenovirus vectors in pancreatic cancer is the relatively limited infection efficiencies achieved *in vitro*.³ Furthermore, *in vivo* gene delivery may be limited by other factors, such as vector's access to target cells through local dissemination or through penetration of vessel walls.

Studies on adenoviral entry into host cells have revealed that two cell surface events, attachment and internalization, are required for an adenovirus to enter a cell.⁴ The viral fiber protein will first attach to the CAR (Coxsackie and adenovirus receptor) on the surface of a host cell.⁵ The virion then enters the cell through the interaction of its penton base with the α v β 3 and α v β 5 integrins on the host cell surface.⁴ Expression of these cell surface markers and their correlation with the efficiency of adenovirus-mediated gene transfer have revealed that the presence of integrins α v β 3,⁶ α v β 5⁷ and CAR^{8,9} are important for an efficient gene transfer and efficacy of

Correspondence: DT Curiel, Division of Human Gene Therapy, Dept of Medicine, Pathology, Surgery and Gene Therapy Center, The University of Alabama at Birmingham, 1824 6th Avenue South, 620 Lurleen Wallace Tumor Institute, Birmingham AL 35294-3300, USA

Received ●●●; accepted ●●●

infection. Recently, a relative lack of CAR on both neoplastic¹⁰ and non-neoplastic¹¹ tissues has been implicated as a limiting factor in successful adenovirus gene transfer.

To overcome the problems associated with *in vitro* and *in vivo* gene delivery to tumor cells, retargeting of adenovirus has been endeavored as a means to improve its specificity and efficacy. Retargeting allows adenovirus to bind to alternative cellular receptors, resulting in CAR-independent infection. One approach is based on immunological retargeting, which uses an antifiber antibody or antibody fragment that is chemically conjugated to either a cell-specific ligand (receptor) or antireceptor antibody. Using this conjugate approach, successful CAR-independent gene transfer has been achieved by targeting viral infection *in vitro* to several cellular receptors including integrins,¹² the folate receptor,¹³ the basic fibroblast growth factor (FGF2) receptor¹⁴ and the epidermal growth factor (EGF) receptor.¹⁰ Retargeting of adenovirus to EGFR was recently shown to enhance gene transfer in primary, low-passage glioma tumor cells as well as in squamous cell carcinoma of the head and neck, which suggests further clinical relevance for retargeting.^{10,15}

A potential disadvantage of this conjugate approach may be the introduction of a degree of complexity to the vector system and the concerns regarding the stability of the virus-conjugate complex under *in vivo* conditions such as systemic administration. Therefore, a genetically modified targeted viral particle might be a more attractive vector candidate for clinical application. Insertion of an Arg-Gly-Asp (RGD) motif into the HI-loop of the adenoviral fiber knob results in efficient CAR-independent infection by allowing binding of the virus to cellular integrins.^{16,17} The vector containing this fiber, AdlucRGD, achieved dramatically augmented gene delivery to several cell types, both *in vitro*¹⁷ and *in vivo*.¹⁸

To direct Ad gene delivery specifically to pancreatic carcinoma cells we chose two approaches. First, we have explored the utility of a bispecific fusion protein formed by a recombinant soluble form of truncated CAR (sCAR) genetically fused with human EGF (sCAR-EGF) to target Ad infection to the EGF receptor expressed on established and primary human pancreatic carcinoma cells. An approach based on employment of soluble viral receptor-EGF fusion proteins has been originally established for targeting retroviral infection to specific cell types.^{19,20} We recently showed that sCAR-EGF fusion protein possesses the ability to effectively retarget the vector via the EGF receptor with enhancement of gene transfer efficiency.²¹ Second, we have shown that recombinant Ad vector containing fibers with RGD motif in the HI loop is capable of augmenting gene delivery to established and primary pancreatic carcinoma cells via a CAR-independent cell entry mechanism using the integrins as receptor. These findings have direct relevance for Ad vector-based gene therapy strategies for pancreatic carcinoma.

Results

Detection of CAR-receptors on primary and established human pancreatic carcinoma cells

It has been shown that human pancreatic carcinoma cell lines are quite refractory to infection of adenovirus vectors due to the low expression level of cell surface mol-

ecules involved in adenovirus infection, ie α v-integrins¹⁶ and the recently identified CAR.³ Therefore, we decided to analyze four established human pancreatic carcinoma cell lines, and two primary human pancreatic carcinoma cells, for cell surface CAR expression by indirect immunofluorescence using an anti-human murine polyclonal serum to CAR. As shown in Figure 1a, both the four pancreatic carcinoma cell lines (BxPC-3, Capan-1, Hs766-T or MIA PaCa-2), as well as the two primary pancreatic carcinoma cells (p6.3 and p10.5) displayed very low levels of cell surface CAR expression. This CAR deficiency strongly suggests a low level of adenovirus-directed gene transfer to these primary and established pancreatic carcinoma cells in case Ad5 vectors with unmodified fiber

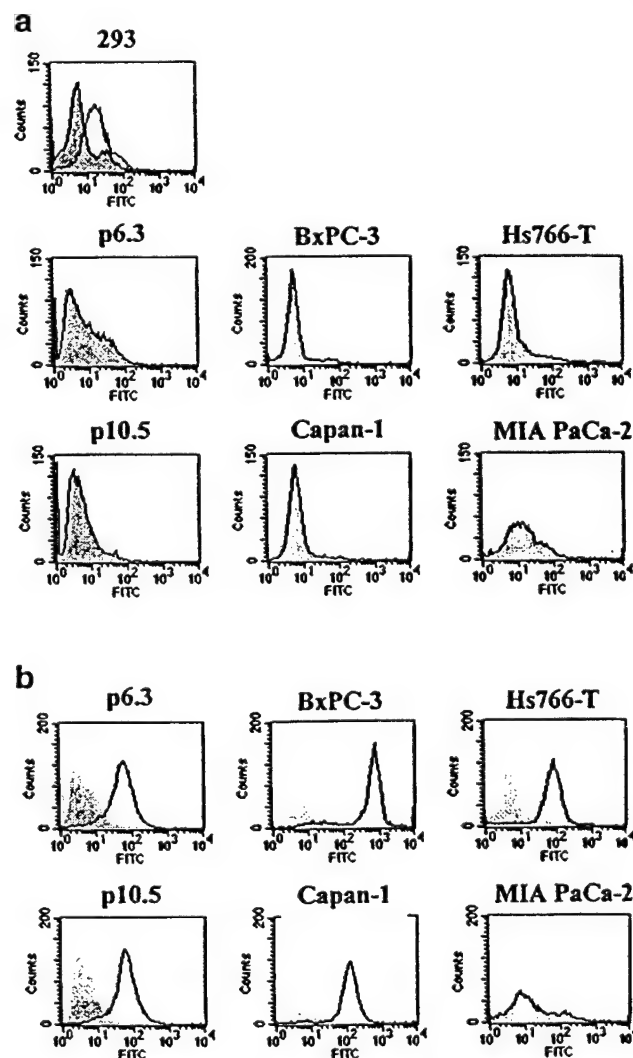


Figure 1 Expression of CAR and EGFR in human pancreatic carcinoma cells. (a) Indirect flow cytometry is shown for the expression of CAR (black line) in the primary human pancreatic carcinoma cells (p6.3 and p10.5), in the established human pancreatic carcinoma cell lines (BxPC-3, Capan-1, Hs766-T and MIA PaCa-2) and in the positive control cell line (293). Normal mouse serum is used as a control (blue peak). (b) Indirect flow cytometry is shown for the expression of EGFR (black line) in the primary human pancreatic carcinoma cells (p6.3 and p10.5) and in established human pancreatic carcinoma cell lines (BxPC-3, Capan-1, Hs766-T and MIA PaCa-2). Normal mouse IgG is used as a control (blue peak).

knobs are used (see below), as has been shown for head and neck cancer²² and for ovarian cancer.²³ On this basis we considered alternative receptors that might be upregulated in pancreatic carcinoma cells and which could be exploited for targeting.

Expression of EGF-receptors on primary and established pancreatic carcinoma cells

The low levels of the native adenovirus receptor CAR in the two primary pancreatic carcinoma cells and the four pancreatic carcinoma cell lines, predicted that they would be refractory to adenovirus infection. Thus, we sought alternative receptors to exploit for targeting. In this regard, the epidermal growth factor (EGF) receptor has shown to be upregulated in a number of human tumors, ie squamous cell carcinoma of the head and neck¹⁵ and in human glioma.¹⁰ Therefore, we evaluated our established pancreatic carcinoma cell lines and the primary pancreatic carcinoma cells for this receptor by flow cytometry using an anti-EGF receptor (EGFR) antibody. Greater than 85% of the cells in three out of four established pancreatic carcinoma cell lines and in both primary pancreatic carcinoma cells analyzed expressed high levels of EGFR (Figure 1b). Based on the observed differences in CAR and EGFR expression levels in pancreatic carcinoma cells (Figure 1), we hypothesized that adenovirus infection would be more efficient if the vector was redirected to EGFR.

EGFR-retargeted gene delivery to primary and established pancreatic carcinoma cells

The high EGFR levels on both the established, as well as the primary, pancreatic carcinoma cells offer a potential target for a modified adenovirus vector that is capable of utilizing this receptor. To demonstrate the utility of EGFR retargeting we fused a recombinant form of truncated CAR (sCAR) with human EGF as a targeting ligand (sCAR-EGF) and investigated its ability to target Ad infection to the EGF receptor overexpressed on pancreatic carcinoma cells. In a previous study Dmitriev *et al*²¹ have shown that sCAR-EGF protein is capable of binding to Ad virions and directing them to EGFR. The sCAR-EGF protein was titrated against Ad to ascertain the optimal ratio of targeting protein to virus as measured by improvements in gene transfer (results not shown). To demonstrate EGFR retargeting, both the established as well as the primary pancreatic carcinoma cells were infected with either native AdCMVLuc or sCAR-EGF-complexed AdCMVLuc or sCAR-6His-complexed AdCMVLuc. sCAR-6His serves as a relevant control protein to show that sCAR-EGF promoted gene transfer occurs by an EGFR-specific mechanism and no enhancement is observed in cells exposed to AdCMVLuc complexed with sCAR-6His, as shown earlier.²¹ Forty-eight hours after infection, cells were lysed and luciferase activity was measured. As shown in Figure 2, compared with AdCMVLuc alone or with AdCMVLuc complexed with sCAR-6His, AdCMVLuc complexed with sCAR-EGF targeting protein mediated 1.5-, two-, three- and five-fold enhancement of luciferase expression in p10.5, p6.3, Capan-1 and BxPC-3 cells, respectively, both using an MOI of 10 and 100. In Hs-766T cells a 1.5-fold enhancement of luciferase expression is only seen at an MOI of 10. Although the expression level of the EGF receptors on MIA PaCa-2 cells appeared to be very low

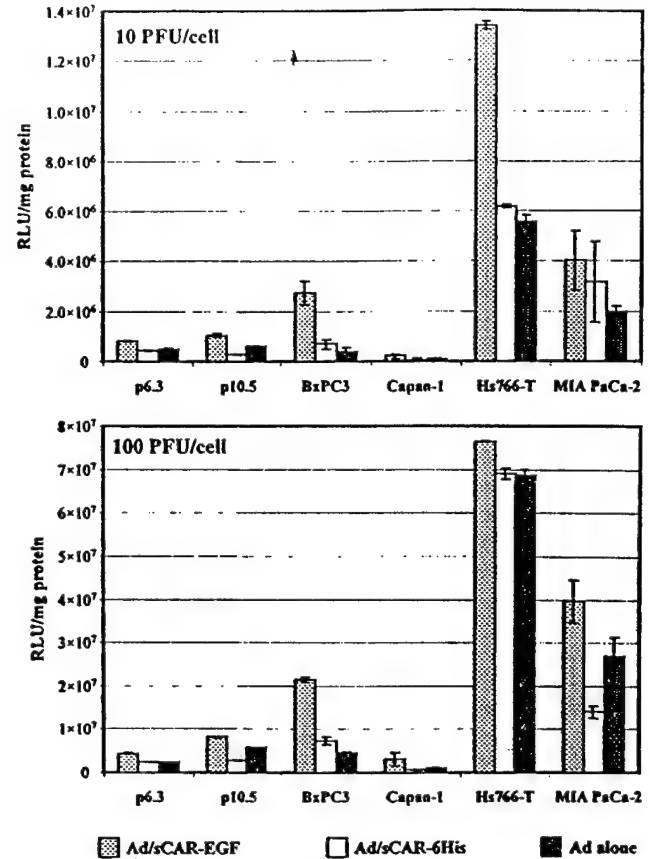


Figure 2 Comparison of EGFR-targeted Ad gene transfer to human pancreatic carcinoma cells. An amount of 3×10^8 p.f.u. of AdCMVLuc was preincubated with either 15 μ g of targeting sCAR-EGF protein (Ad/sCAR-EGF \square) or with 12 μ g of sCAR-6His as a control (Ad/sCAR-6His \square) or with PBS (Ad alone \blacksquare) before incubation with cells. Then monolayers of primary pancreatic carcinoma cells (p6.3 and p10.5), as well as established pancreatic carcinoma cell lines (BxPC-3, Capan-1, Hs 766-T and MIA PaCa-2) were exposed to Ad or Ad/sCAR-ligand complexes at MOI (10 or 100 p.f.u./cell) for 1 h at 37°C. Infection medium was changed for complete medium and the cells were incubated for 48 h at 37°C. The cells were lysed, the protein concentration and luciferase activities of the lysates were determined. The relative light units (RLU) of luciferase/milligram of total cellular protein are shown graphically. The results are shown as the mean of multiple assays. Each point represents the mean \pm standard deviation of two determinations. Error bars, s.e.

(Figure 1b), still a 1.5-fold enhancement of luciferase expression is observed using AdCMVLuc complexed with sCAR-EGF (Figure 2). These results demonstrated that sCAR-EGF targeting protein enables retargeting of Ad vector with several-fold enhancement of gene transfer efficiency specifically to EGFR-positive pancreatic carcinoma cells (both primary and established cell lines). The sCAR-EGF promoted gene transfer occurs by an EGFR-specific mechanism, since no significant enhancement was observed in cells exposed to AdCMVLuc complexed with sCAR-6His (untargeted Ad). Furthermore, the specificity of sCAR-EGF-mediated Ad-targeting was illustrated by failure of the sCAR-EGF to enhance Ad-based gene transfer to EGFR-negative human mammary gland (MDA-MB-453) cells (results not shown; Ref. 21).

Expression of $\alpha v \beta 3$ and $\alpha v \beta 5$ integrins on primary and established pancreatic carcinoma cells

Because EGFR retargeting by sCAR-EGF enhanced adenovirus gene transfer with variable efficiency and

with relatively low retargeting indexes (range of enhancement of 1.5- to five-fold, Figure 2), as compared with human squamous carcinoma (SCC-4) cells and human epidermoid carcinoma (A-431) cells,²¹ we looked for targeting via other cellular receptors. It has been shown that insertion of an Arg-Gly-Asp (RGD) motif in the HI-loop of the Ad5 knob domain resulted in a viral fiber protein which results in efficient CAR-independent infection by allowing binding of Ad to cellular integrins.¹⁷ The vector containing this fiber (AdlucRGD) indeed achieved augmented gene delivery to several cell types by interaction to cellular α v integrins and thus allowing CAR-independent infection.^{17,18} We already determined the low level of expression of the native CAR receptor on the surface of established and primary pancreatic carcinoma cells (Figure 1). Therefore, to assess if a genetically modified Ad containing an RGD motif can efficiently enter the pancreatic carcinoma cells, we ascertained the level of expression of both α v β 3 and α v β 5 integrins on these tumor cells. Flow cytometry was performed to detect expression of both α v β 3 and α v β 5 integrins on established and primary pancreatic carcinoma cells by indirect immunofluorescence using LM609 and P1F6 mAbs, respectively. As shown in Figure 3, expression of α v β 3 integrin is absent in p6.3, BxPC-3 and Capan-1 cells, while a low to moderate α v β 3 expression is seen in p10.5, Hs766-T, MIA PaCa-2 cells. Integrin α v β 5, on the other hand, is present on all pancreatic cancer cells: p6.3, p10.5 and Capan-1 cells express high levels of α v β 5, while the other pancreatic carcinoma cell lines (BxPC-3, Hs766-T, MIA PaCa-2) express moderate levels of this integrin. Thus, the presence of one or both of the α v integrins on the established and primary pancreatic carcinoma cells should allow CAR-independent gene transfer by AdlucRGD.

Integrin targeted gene delivery to primary and established pancreatic carcinoma cells

Our next goal was to examine whether introduction of the RGD motif in the fiber of AdlucRGD resulted in enhancement of this virus to infect established and primary pancreatic carcinoma cells. Therefore, AdlucRGD

was utilized for an assay based on competitive inhibition of Ad-mediated gene delivery by recombinant Ad5 fiber knob protein, known to efficiently block virus binding to CAR.¹⁷ To demonstrate CAR-independent cell entry by AdlucRGD, established and primary pancreatic carcinoma cells were infected with various MOIs with either native AdCMVLuc or integrin-retargeted AdlucRGD in the presence or absence of blocking knob protein. Forty-eight hours after the infection, cells were lysed and luciferase activity was measured. As shown in Figure 4a in both established as well as primary pancreatic carcinoma cells, striking differences between the infection profiles were demonstrated by these two viruses at each MOI. Luciferase expression in the AdlucRGD-infected primary pancreatic carcinoma cells was 100- to 500-fold higher than in the cells infected with AdCMVLuc. Even in the established pancreatic carcinoma cell lines the difference in infection efficiencies demonstrated by these two viral vectors was still between 10- and 100-fold. Of note, comparison of luciferase expression upon infection of 293 cells (high CAR expression) with AdCMVLuc versus AdlucRGD did not reveal a substantial enhancement of gene transfer with the AdlucRGD-targeted virus (results not shown).

Furthermore, AdCMVLuc-mediated infection in the presence of Ad5 fiber knob protein revealed a dramatic inhibition. The knob blocked between 55% and 95% of the gene transfer at MOIs of 10 and 100 p.f.u. per primary pancreatic carcinoma cells, while this protein blocked between 40% and 90% of the gene transfer at MOIs of 1, 10 and 100 p.f.u. per established pancreatic carcinoma cell line (Figure 4b). Most importantly, for the primary p10.5 pancreatic carcinoma cells as well as the established Capan-1, Hs766-T and MIA PaCa-2 pancreatic cell lines, recombinant knob protein did not reveal any significant inhibition effect on the levels of luciferase expression directed by AdlucRGD (Figure 4b). Strong inhibition by the fiber knob on AdCMVLuc-mediated luciferase expression suggests that the fiber-CAR interaction is the only pathway this virus can use to infect pancreatic carcinoma cells.

Gene delivery of an integrin-targeted Ad vector increases the frequency of infection of pancreatic carcinoma cells

The previous experiments demonstrated that adenovirus infection of both primary and established pancreatic carcinoma cells can be redirected to the α v-integrins via a CAR-independent pathway, resulting in enhanced reporter gene expression. This observed enhancement of gene transfer with the AdlucRGD virus could have arisen from either a few transduced cells exhibiting more abundant gene expression because an increased number of viruses have infected these cells or from a greater number of pancreatic carcinoma cells that may have been rendered susceptible to infection because of the high amount of expressed α v-integrins on the cell surface. To identify the nature of the enhanced gene expression CAR-independent retargeting was performed using an adenovirus that expressed the green fluorescent protein (GFP) reporter gene. Both primary, as well as established, pancreatic carcinoma cells were infected with either native AdGFP or with the genetically modified AdGFP-RGD at an MOI of 10, 100 and 1000 per cell during 48 h and the number of infected cells were monitored by fluorescent

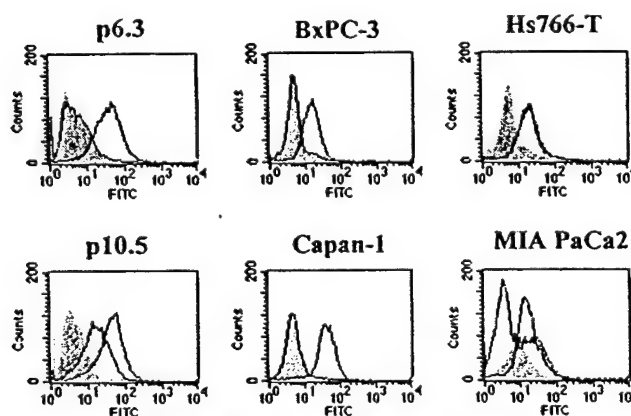


Figure 3 Expression of α v-integrins in human pancreatic carcinoma cells. Indirect flow cytometry is shown of the expression of α v β 3-integrins (black line) and α v β 5-integrins (red line) in primary human pancreatic carcinoma cells (p6.3 and p10.5) and in established human pancreatic carcinoma cell lines (BxPC-3, Capan-1, Hs766-T and MIA PaCa-2). Normal mouse IgG is used as a control (blue peak).

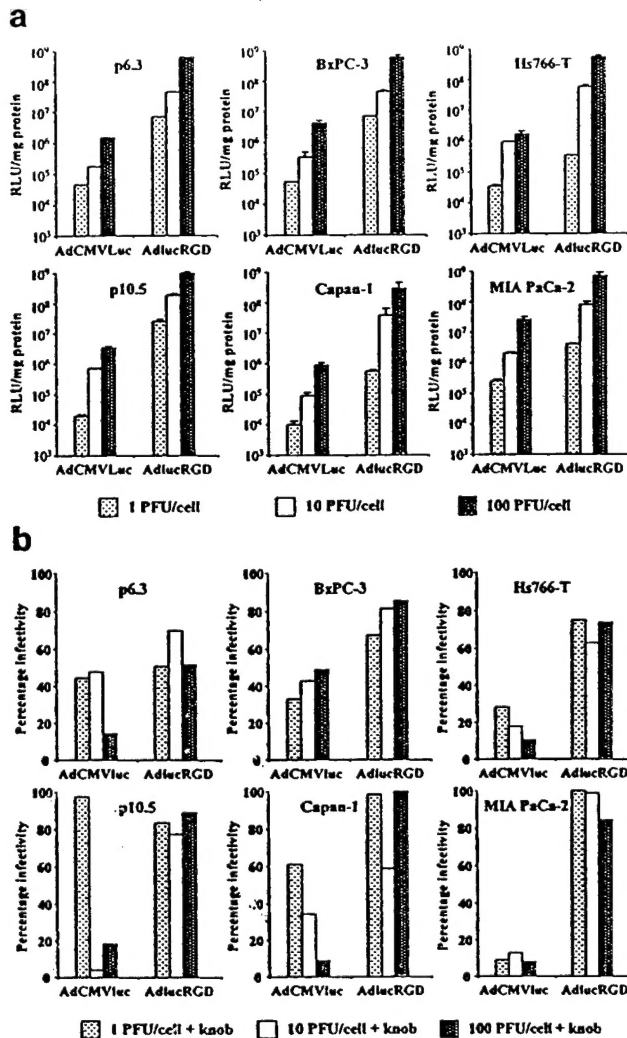


Figure 4 Comparison of Ad gene transfer efficiencies of AdCMVLuc and AdlucRGD to the human pancreatic carcinoma cells. (a) Primary human pancreatic carcinoma cells: p6.3 and p10.5 and established human pancreatic carcinoma cell lines BxPC-3, Capan-1, Hs766-T and MIA PaCa-2 were infected with AdCMVLuc or AdlucRGD at an MOI of 1 (■), 10 (□), and 100 (■) p.f.u./cell. Infection medium was changed for complete medium 1 h after infection and the cells were incubated for 28 h at 37°C. The cells were lysed, the protein concentration and luciferase activity of the lysates were determined. The relative light units (RLU) of luciferase/milligram of total cellular protein are shown graphically. The results are shown as the mean of multiple assays. Each point represents the mean \pm standard deviation of two determinations. (b) Primary human pancreatic carcinoma cells: p6.3 and p10.5 and established human pancreatic carcinoma cell lines BxPC-3, Capan-1, Hs766-T and MIA PaCa-2 were preincubated in PBS or PBS containing recombinant Ad5 fiber knob protein for 30 min at 37°C. AdCMVLuc or AdlucRGD were added to the cells at an MOI of 1 (■), 10 (□), and 100 (■) p.f.u./cell for 1 h, then media was changed and the cells were incubated at 37°C. At 48 h after infection the cells were lysed, the protein concentration and luciferase activity of the lysates were determined. The percentages of luciferase activity detected in the cells infected in the presence of knob calculated with regard to luciferase activity detected in the cells infected in the absence of knob (=100%, not shown on the graph) are depicted graphically.

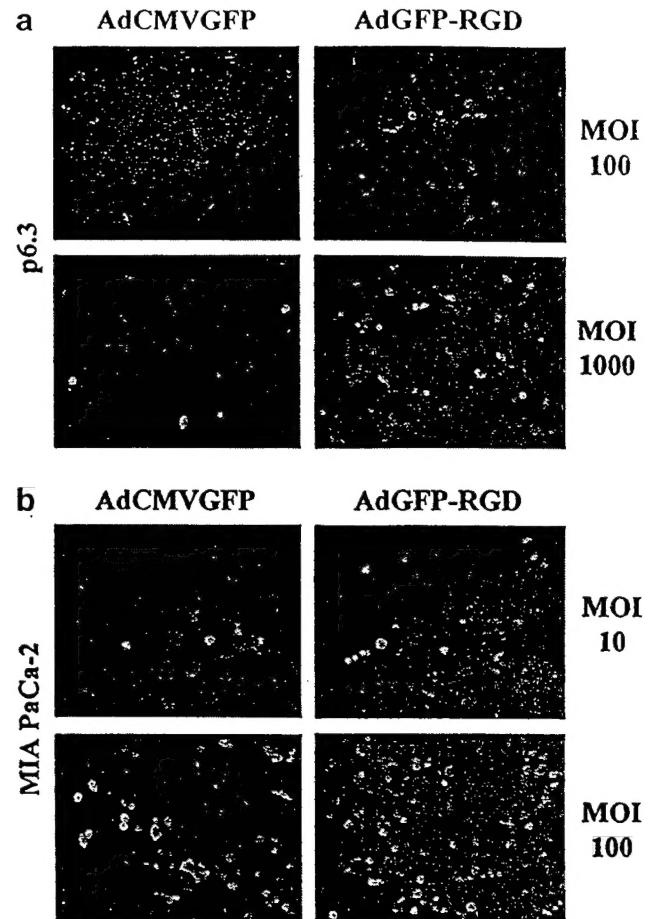


Figure 5 Analysis of the number of infected pancreatic carcinoma cells using AdCMVGFP and AdGFP-RGD. (a) Infection of the primary pancreatic carcinoma cells (p6.3) was performed at an MOI of 100 or 1000 v.p./cell and (b) the established pancreatic carcinoma cell line (MIA PaCa-2) was infected at an MOI of 10 or 100 p.v./cell. Forty-eight hours after infection the percentage of infected cells was determined using the fluorescence microscope.

amount of pancreatic carcinoma cells were infected, while retargeting via the α v-integrins by the CAR-independent route using AdGFP-RGD resulted in increased numbers of cells that were positive for green fluorescent protein expression both for the p6.3 primary cells (Figure 5a) as well as for the MIA PaCa-2 established pancreatic carcinoma cell line (Figure 5b). As a control, infection of 293 cells (high CAR expression) with AdCMVGFP and AdGFP-RGD viruses revealed a significant lower percentage of gene transfers with AdGFP-RGD compared with untargeted AdCMVGFP (data not shown). These data indicate that retargeting of the adenovirus to the α v-integrins via a CAR-independent cell entry increased the number of infected pancreatic carcinoma cells instead of showing more abundant gene expression in the infected cells.

Discussion

Human pancreatic carcinoma cell lines have been shown to be relatively resistant to adenovirus mediated gene transfer. These unmodified, first-generation adenovirus vectors have failed to deliver genes at an efficiency that

microscopy. Figure 5 reveals the results of retargeting via the α v-integrins of two representative pancreatic carcinoma cells: the p6.3 primary pancreatic carcinoma cells and the established pancreatic carcinoma cell line MIA PaCa-2. Using the native AdCMVGFP virus only a low

would be therapeutically in the context of human pancreatic cancer. Pearson *et al*¹³ revealed that the low expression levels of the integrins $\alpha v\beta 3$, $\alpha v\beta 5$, $\alpha 5$, $\beta 1$ and CAR will limit adenovirus-mediated gene transfer in both lung and pancreatic cancer cell lines and their results were confirmed in this study. Importantly, the two primary (passage number lower than five) human pancreatic carcinoma cells (p6.3 and p10.5) used in this study were revealed to be refractory to adenoviral infection to the same amount as the established, highly passaged pancreatic carcinoma cell lines. For this reason, in this report, we have demonstrated two ways of retargeting of adenovirus vectors as a means to enhance gene transfer efficiency to both primary and established human pancreatic carcinoma cells. First, we showed that EGFR-retargeted entry pathway using the sCAR-EGF protein, which binds to Ad virions and redirects them to EGFR,²¹ was able to enhance the gene transfer efficiency of pancreatic carcinoma cells between 1.5- and five-fold, most likely via a non-CAR pathway. Increase of gene transfer by retargeting to EGFR is explained by flow cytometry analyses which revealed that EGFR is overexpressed in both primary, as well as established, pancreatic carcinoma cells. It is very likely that redirecting the virus to the highly expressed EGFR molecule increased the overall number of cells infected, thereby leading to an enhanced gene transfer, as has been shown for head and neck cancer cells.¹⁵ Of importance, immunohistochemical staining of normal and adenocarcinoma pancreatic tissue slides (resection material from patients) with anti-EGFR antibody revealed a moderate to high expression level of EGFR molecules on most (adeno)carcinoma cells of the pancreas compared with the surrounding normal pancreas or normal liver cells (unpublished observations). Therefore, it is not likely that EGFR-targeted Ad vectors will cause any significant toxicity to non-diseased pancreatic-liver tissue. The increase in gene transfer shown here for pancreatic carcinoma is significantly lower than seen by Dmitriev *et al*²¹ who revealed that Ad encoding luciferase complexed with sCAR-EGF targeting protein mediated a much higher enhancement of luciferase gene expression in EGFR-positive SKOV3.ip1 (human ovarian carcinoma) cells, EGFR-positive SCC-4 (human squamous carcinoma) cells and EGFR-positive A-431 (human epidermoid carcinoma) cells. This difference is most likely explained by the higher number and/or expression level of the EGF-receptors on these SKOV3.ip1, SCC-4 and A-431 cells compared with the primary and established pancreatic carcinoma cells. Despite the conceptual gains realised by this conjugate approach, this 'two-component' strategy introduces a degree of complexity to the vector system. Moreover, it raises concerns regarding the stability of the virus-conjugate complex under certain *in vivo* conditions.¹⁸ Therefore, we decided to exploit another targeting approach.

Genetically modified vectors containing short peptide targeting sequences at the C-terminus of the adenoviral knob domain (which binds to CAR) have been produced, which revealed expanded viral tropism *in vitro* by targeting to, for example, integrins.²⁴ However, the C-terminus of the knob domain is located at the base which is not an ideal position to interact efficiently with cellular receptors. Recently it has been reported that the use of an alternate region of the knob domain, the HI-loop, is a more rational site for inserting targeting motifs.¹⁶ This

region is not directly involved in trimerization, it contains mostly hydrophilic amino acids and is of different length in different Ad serotypes. Furthermore, the HI-loop is flexible and is exposed on the exterior of the knob. Insertion of an RGD motif in this region resulted in a viral fiber protein which results in efficient CAR-independent infection by allowing binding of Ad to cellular integrins.¹⁷ The use of RGD-modified viral vectors (AdlucRGD and AdGFP-RGD) in this study is based on flow cytometry data using anti-CAR and anti- $\alpha v\beta 3/\alpha v\beta 5$ antibodies which revealed no expression of CAR, but shows the presence of at least one of the αv -integrins on the surface of the primary and established pancreatic carcinoma cells. The resulting modified virus (AdlucRGD) revealed a dramatic increase in gene transfer efficiency of both primary and established pancreatic carcinoma cells.^{16,17} The absence of CAR expression and the presence of the αv -integrins on the surface of these cells explains the enhanced luciferase expression of AdlucRGD compared with parental AdCMVLuc. Furthermore, the ability of the knob protein to block infection using parental AdCMVLuc as well as the lack of inhibition in the presence of this knob protein on the levels of luciferase expression directed by AdlucRGD, clearly demonstrated that RGD-modified Ad has enhanced binding to pancreatic carcinoma cells lacking CAR, leading to enhanced gene expression. The observation that knob inhibited luciferase expression of AdlucRGD in p6.3 cells and to a lesser extent in BxPC-3 cells, suggests that in these particular pancreatic carcinoma cells either knob may interfere with binding of AdlucRGD to the integrins or that a minor fraction of AdlucRGD enters these cells via the CAR.

Of note, infection of pancreatic carcinoma cells with AdGFP-RGD revealed that the number of infected pancreatic carcinoma cells has been increased rather than a few cells exhibiting more abundant gene expression as compared with parental AdGFP. The importance of both latter findings lay in the fact that fewer AdRGD virus particles need to be administered *in vivo* to obtain the same therapeutic effect, thereby decreasing the vector-related toxicity. Importantly, although Ad5lucRGD has expanded tropism,¹⁸ this genetically modified virus is not tumor-specific. However, in a study where both primary ovarian tumor explants, as well as nontumor mesothelial tissue samples, from patients were infected with Adluc and AdlucRGD, the mesothelial tissue samples expressed low luciferase activity both with the Ad5lucRGD vector as with AdCMVLuc.²³ Therefore, studies will be initiated to assess the efficacy of infection of normal pancreatic epithelial cells obtained from human resection material with Ad targeted to EGFR, as well as Ad targeted to integrins (AdlucRGD).

To our knowledge this is the first study where enhanced gene transfer by EGFR, as well as integrin-targeted adenovirus vectors has been demonstrated in primary pancreatic carcinoma cells. Of note, the infection conditions were selected for representing a high level of stringency that a gene transfer vector would have to overcome in the clinical context. The observed level of enhancement as seen with the EGFR-retargeted vector to a minor extent and with the RGD-modified Ad vector to a major extent, would thus support the use of these vectors in human gene therapy clinical trials for pancreatic carcinoma. Thus, this study seeks to validate a strategy

that will address a critical shortcoming in cancer gene therapy. The key finding in this study is that gene transfer to both primary pancreatic cancer cells, as well as established pancreatic carcinoma cell lines, is significantly enhanced by utilizing an RGD-modified retargeted vector. As integrins have been frequently shown to be overexpressed by various epithelial tumors, as described for head and neck cancer²² and ovarian cancer,²³ our novel vector strategy could potentially be exploited in the context of pancreatic cancer. Most importantly, the levels of gene transfer of the RGD-modified adenovirus in surrounding nontumor pancreatic epithelial cells provides a rationale for further studies with this targeted vector in preclinical efficacy studies that would lead to human clinical trials.

Materials and methods

Tumor cells

The established human pancreatic carcinoma cell lines (BxPC-3, Capan-1, Hs766-T and MIA PaCa-2; >20 passages) were purchased from Boehringer Ingelheim, Belgium. These cells were cultured in Dulbecco's minimal essential medium (DMEM) (Mediatech, Herndon, VA, USA) with 10% fetal bovine serum (FBS) (Summit Biotechnology, Ft Collins, CO, USA), 1% L-glutamine and 1% penicillin/streptomycin (Gibco BRL, Life Technologies, Rockville, MD, USA). The primary human pancreatic carcinoma cells (p6.3 and p10.5; <5 passages) were obtained from Dr E Jaffee, Johns Hopkins University School of Medicine, Baltimore, MD, USA. All cell lines were cultured at 37°C in 5% carbon dioxide atmosphere.

Viruses, antibodies and recombinant proteins

The E1-, E3-deleted adenovirus vector expressing the firefly luciferase from the cytomegalovirus (CMV) immediate-early promoter, AdCMVLuc²⁵ was obtained from Robert Gerard (University of Leuven, Leuven, Belgium). Ad vector AdlucRGD, containing recombinant fiber-RGD protein and expressing firefly luciferase was generated by transfection of 293 cells with *PacI*-digested pVK703.¹⁸ Ad vector AdCMVGFP, encoding green fluorescent protein, and AdGFP-RGD, containing recombinant fiber-RGD protein and expressing GFP were obtained from Dr M Parameshwar (University of Alabama at Birmingham, AL, USA). Viruses were propagated and plaque-titered on the permissive cell line 293 and purified by double cesium chloride gradients.²⁶ Virus preparations were dialyzed against phosphate-buffered saline (PBS), aliquoted, and stored at -80°C. Titers were determined using standard plaque assays and the number of viral particles was determined by measuring the optical density at 260 nm. For AdCMVLuc: 4.2×10^{11} p.f.u./ml and 8.1×10^{12} v.p./ml (v.p. to p.f.u. ratio: 19.3) and for AdlucRGD: 5.6×10^{10} p.f.u./ml and 1.7×10^{11} v.p./ml (v.p. to p.f.u. ratio: 32.9).

Murine polyclonal serum to baculovirus-produced human soluble CAR protein were generated at the University of Alabama at Birmingham, Hybridoma Core Facility. Murine mAb 425 to human EGFR was a generous gift from Zenon Steplewski (Thomas Jefferson University, Philadelphia, PA, USA) and was described earlier.²⁷ Murine mAb LM609 to $\alpha\beta 3$ integrin and P1F6 to $\alpha\beta 5$ integrin were purchased from Chemicon

(Temecula, CA, USA). Recombinant fiber knob from Ad5 was obtained from Dr V Krasnykh (University of Alabama at Birmingham). Recombinant sCAR-6His and sCAR-EGF proteins were constructed as described.²¹

Flow cytometry

Confluent cells were released with versene or cell dissociation buffer (Gibco BRL, Life Technologies) or by trypsinizing of the cells using 0.05% trypsin/0.53 mM EDTA for 3 min or less (2 ml per T75 flask). The trypsinized cells were quenched with 10-fold volume of cold DMEM-medium containing 10% fetal bovine serum and pelleted at 1200 r.p.m. for 5 min. Cells were resuspended in cold PBS with 1% bovine serum albumin (BSA) and counted. Cells were spun (1200 r.p.m. for 5 min) and aliquoted in PBS + BSA at 2×10^6 cells/ml. Cells (2×10^5) were incubated with either mAb 425 (5 μ g/ml) (anti-EGFR) or with murine anti-CAR serum (1:250) or with murine mAb LM609 (anti- $\alpha\beta 3$) or with mAb P1F6 (anti- $\alpha\beta 5$) for 1 h at 4°C. A normal murine serum and control IgG were used as a negative control. Cells were then washed with buffer and incubated with secondary FITC-labeled goat anti-mouse immunoglobulin G (Jackson, West Grove, PA, USA) at a concentration of 5 μ g/ml for 1 h at 4°C. After washing, 10^4 cells per sample were analyzed using flow cytometry performed at the University of Alabama at Birmingham FACS Core Facility. Data were expressed as the geometric mean fluorescence intensity of the entire gated population. The positive population cells was determined by gating the right-hand tail of the distribution of the negative control sample for each individual cell line at 2%. This gate setting was then used to determine the percentage of CAR-, $\alpha\beta 3$ -, $\alpha\beta 5$ - or EGFR-positive cells in each individual cell line.

Adenovirus vector-mediated gene transfer

To assess native or EGFR-retargeted adenovirus infection efficiency, 5×10^4 cells were plated in 24-well plates and allowed to adhere overnight at 37°C. An amount of 3×10^8 p.f.u. of AdCMVLuc was preincubated with either 15 μ g of sCAR-EGF protein or 12 μ g of sCAR-6His as a control or with PBS, before incubation with cells for 30 min at room temperature. Then monolayers of pancreatic carcinoma cells were exposed to Ad/sCAR-ligand complexes and Ad without ligand complexes at various MOIs (10 and 100 p.f.u. cell) for 1 h at 37°C. The virus was removed and the cells were incubated for 48 h in complete media.

To assess native or RGD-modified adenovirus efficiency, 5×10^4 cells were plated in 24-well plates and allowed to adhere overnight at 37°C. To demonstrate the specificity of infection, half of the cells were blocked with recombinant Ad5 knob protein (10–15 μ g/well, diluted in PBS) for 30 min at 37°C and the other half were incubated with PBS as a control. Subsequently, both the blocked cells, as well as the unblocked cells, were infected with native AdCMVLuc or AdlucRGD at various MOIs (1, 10 and 100) per cell for 1 h at 37°C. The virus was removed and the cells were incubated for 48 h in complete media.

Cell lysates were assayed for luciferase expression 48 h after infection in a Berthold Luminometer using the Luciferase Assay System (Promega, Madison, WI, USA), and the protein concentration was determined using the

Pierce Protein Assay according to the manufacturer's protocols.

To evaluate the number of transfected cells, 5×10^4 cells were plated in 24-well plates and allowed to adhere overnight at 37°C. The cells were infected with AdCMVGFP and AdGFP-RGD at various MOIs (10, 100 and 1000) per cell for 1 h at 37°C. The virus was removed and the cells were incubated for 48 h in complete media. Subsequently, the media was removed and PBS was added to the wells and the percentage of infected cells were visualized under a fluorescence microscope.

Acknowledgements

This work was supported from grants by the National Institute of Health RO1 CA 74242, RO1 HL 50255, National Cancer Institute NO1 CO-97110 and training grant IT32 CA75930 to David T Curiel, M.D., and Department of the Army Grant DAMD 17-00-1-0115 to Igor Dmitriev, Ph.D. In addition, this work was supported from grants by the European Gastro-Surgical School (EPGS) at the Academic Medical Center of the University of Amsterdam and by the Netherlands Organization for Scientific Research (NWO). Michel van Wijland is acknowledged for assistance preparing the manuscript.

References

- Humphreys MJ, Greenhalf W, Neoptolemos JP, Ghaneh P. The potential for gene therapy in pancreatic cancer. *Int J Pancreatol* 1999; 26: 5-21.
- Von Hoff DD, Goodwin AL, Garcia L. Advances in treatment of patients with pancreatic cancer: improvement in symptoms and survival time. *Br J Cancer* 1998; 78: 9-13.
- Pearson AS et al. Factors limiting adenovirus-mediated gene transfer into human lung and pancreatic cancer cell lines. *Clin Cancer Res* 1999; 5: 4208-4213.
- Wickham TJ, Mathias P, Cheresch DA, Nemerov GR. Integrins $\alpha v \beta 3$ and $\alpha v \beta 5$ promote adenovirus internalization, but not virus attachment. *Cell* 1993; 73: 309-319.
- Bergelson JM et al. Isolation of a common receptor for coxsackie B viruses and adenoviruses 2 and 5. *Science* 1997; 275: 1320-1323.
- Huang S, Endo RL, Nemerov GR. Upregulation of integrins $\alpha v \beta 3$ and $\alpha v \beta 5$ on human monocytes and T lymphocytes facilitate adenovirus-mediated gene delivery. *J Virol* 1995; 69: 2257-2263.
- Goldman MJ, Wilson JM. Expression of $\alpha v \beta 5$ integrin is necessary for efficient adenovirus-mediated gene transfer in the human airway. *J Virol* 1995; 69: 5951-5958.
- Hemmi S et al. The presence of human coxsackievirus and adenovirus receptor is associated with efficient adenovirus-mediated transgene expression in human melanoma cell cultures. *Hum Gene Ther* 1998; 9: 2363-2373.
- Li Y et al. Loss of adenoviral receptor expression in human bladder cancer cells: a potential impact on the efficacy of gene therapy. *Cancer Res* 1999; 59: 325-330.
- Miller CR et al. Differential susceptibility of primary and established human glioma cells to adenovirus infection: targeting via the epidermal growth factor receptor achieves fiber receptor-independent gene transfer. *Cancer Res* 1998; 58: 5738-5748.
- Zabner J et al. Lack of high affinity fiber receptor activity explains the resistance of ciliated airway epithelia to adenovirus infection. *J Clin Invest* 1997; 100: 1144-1149.
- Wickham TJ et al. Targeted adenovirus gene transfer to endothelial and smooth muscle cells by using bispecific antibodies. *J Virol* 1996; 70: 6831-6838.
- Douglas TJ et al. Targeted gene delivery by tropism-modified adenoviral vectors. *Nat Biotechnol* 1996; 14: 1574-1578.
- Goldman CK, Rogers BE, Douglas JT, Curiel DT. Targeted gene delivery to Kaposi's sarcoma cells via the fibroblast growth factor receptor. *Cancer Res* 1997; 57: 1447-1451.
- Blackwell JL et al. Retargeting to EGFR enhances adenovirus infection efficiency of squamous cell carcinoma. *Arch Otolaryngol Head Neck Surg* 1999; 125: 856-863.
- Krasnykh V et al. Characterization of an adenovirus vector containing a heterologous peptide epitope in the HI loop of the fiber knob. *J Virol* 1998; 72: 1844-1852.
- Dmitriev I et al. An adenovirus vector with genetically modified fibers demonstrates expanded tropism via utilization of a coxsackievirus and adenovirus receptor-independent cell entry mechanism. *J Virol* 1998; 72: 9706-9713.
- Reynolds PN, Dmitriev I, Curiel DT. Insertion of an RGD motif into the HI loop of adenovirus fiber protein alters the distribution of transgene expression of the systemically administered vector. *Gene Therapy* 1999; 6: 1336-1339.
- Boerger AL, Snitkovsky S, Young JAT. Retroviral vectors preloaded with a viral receptor-ligand bridge protein are targeted to specific cell types. *Proc Natl Acad Sci USA* 1993; 90: 9867-9872.
- Snitkovsky S, Young JAT. Cell-specific viral targeting mediated by a soluble retroviral receptor-ligand fusion protein. *Proc Natl Acad Sci USA* 1998; 95: 7063-7068.
- Dmitriev I et al. Ectodomain of Coxsackievirus and adenovirus receptor genetically fused to epidermal growth factor mediates adenovirus targeting to epidermal growth factor receptor-positive cells. *J Virol* 2000; 74: 6875-6884.
- Kasano K et al. Selective gene delivery to head and neck cancer via αn integrin targeted adenoviral vector. *Clin Cancer Res* 1999; 5: 2571-2579.
- Vanderkwaak TJ et al. An advanced generation of adenoviral vectors selectively enhances gene transfer for ovarian cancer gene therapy approaches. *Gynecol Oncol* 1999; 74: 227-234.
- Wickham TJ et al. Increased *in vitro* and *in vivo* gene transfer by adenovirus vectors containing chimeric fiber proteins. *J Virol* 1997; 71: 8221-8229.
- Herz J, Gerard RD. Adenovirus-mediated transfer of low density lipoprotein receptor gene acutely accelerates cholesterol clearance in normal mice. *Proc Natl Acad Sci USA* 1993; 90: 2812-2816.
- Graham FL, Prevec L. Manipulation of adenovirus vectors. In: Murray EJ, Walker JM (eds). *Molecular Biology, Gene Transfer and Expression Techniques*. Humana Press: Totawa, NJ, 1991, pp 109-128.
- Murthy U et al. Binding of an antagonist monoclonal antibody to an intact and fragmented EGF-receptor polypeptide. *Arch Biochem Biophys* 1987; 252: 549-560.